Meso- and Microscale Patterns of Fusarium Head Blight in Spring Wheat Fields in Minnesota

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ABSTRACT

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Several techniques were used to study the spatial distribution of Fusarium head blight (FHB) in spring wheat fields in the Red River Valley of Minnesota in 2001 and 2002. Four scales of study were analyzed, ranging from countywide comparisons down to adjacent heads. Agreement to frequency distributions and the departure from randomness, along with the autocorrelation of FHB clusters, were calculated at each scale. Regression analysis also was used to describe any edge effects that might exist. Finally, the optimal number of samples to adequately assess a 32.4-ha (80-acre) field was determined to a precision of $\pm 5\%$ disease incidence (DI). The analysis showed that DI had a random pattern at scales smaller than 32.4-ha fields, including quadrats of 6,561, 729, and 9 m², as well 0.8-m transects involving consecutive heads within drill rows. There was no difference in DI associated with edges of fields compared with the incidence of FHB in transects within fields. Analysis of the spatial distribution at the mesoscale (county and township) showed no association in FHB DI between fields based on proximity. Differences were attributed to previous crop and in-field residue. Disease incidence was most accurately assessed on a field-by-field basis. The optimal sampling size (with $< 5\%$ error) for surveying for the incidence of FHB in a standard commercial field was seven 20-head samples. Regional disease estimates would improve from including more fields at the expense of fewer samples per field.

Fusarium head blight (FHB) is one of the most devastating cereal diseases in the Red River Valley of Minnesota and North Dakota. In this region, *Fusarium graminearum* Schwabe is the primary pathogen associated with Fusarium head blight. FHB causes losses on all cereal crops grown in this area, including durum wheat and barley (23) and, to a lesser extent, oat (17). *F. graminearum* also causes a stalk rot of corn (30). Epidemics in 1993–94 in this region resulted in estimated yield losses of 176 million bushels valued at \$704 million (23). *F. graminearum* causes losses directly by physically damaging kernels and by causing florets to abort. Infected grain that can be harvested frequently is lowered in test weight and reduced in quality due to the concomitant production of the mycotoxin deoxynivalenol (17) by the fungus. Historical epidemics of FHB in the United States and Canada were reviewed by Atanasoff (1) and Sutton (26).

Growers manage FHB with an integrated approach (2). The primary management practices recommended by the University of Minnesota are tillage and rotation with broadleaf crops (28). These recommendations are based on the association of FHB severity with infected corn or small grain residue (1,8,15,26). The use of the most resistant cultivars also is recommended. Currently, however, there are no highly resistant spring wheat cultivars available (17,28). Chemical control sometimes is employed as a single fungicide application at anthesis in order to control floret infection caused by ascospores of the teleomorph, *Gibberella zeae* (Schwein.) Petch. Ascospores represent the primary inoculum and it is theorized that FHB behaves like a monocyclic disease (26). Results of chemical control studies have been inconsistent (16), however, and fungicide sprays for control of FHB remain both insufficient and expensive.

The lack of both resistant cultivars and consistent chemical control has placed emphasis on cultural management practices, including crop rotation and tillage (8). However, these practices are becoming more difficult for producers to employ. For example, crop rotations are getting shorter and, in many regions, susceptible crops such as corn and barley are the main rotation alternatives. In addition, government incentives promote reduced-tillage farming (8,23). Due to the shortcomings of individual FHB control practices, a better under-

standing of disease development and assessment methodology may lead to more effective application of the integrated control measures.

Analysis of the spatial distribution of diseased plants has been used to provide insight into what factors influence the development of plant diseases (4–6,22,27), determine where inoculum may have originated (6, 22), and develop sampling strategies for management decisions (3,14,18). Analysis of the spatial distribution of FHB at the regional and local levels may help elucidate the relative effects of weather, crop rotation, and other management practices, including tillage, on FHB incidence. The results from this analysis could be useful in designing survey protocols for FHB at the soft-dough stage of grain development at the local or regional level. Sampling procedures also have implications for researchers designing small plot experiments who must weigh time and labor costs against precision and accuracy goals to quantify FHB in the field. The purpose of this study was to determine the spatial distribution of FHB in spring wheat on scales from multiple townships and counties down to adjacent heads, and then to develop an appropriate sampling protocol to determine regional and local disease incidence.

MATERIALS AND METHODS

Scales of study. Four scales of study were evaluated in the Red River Valley of Minnesota in 2001 and 2002. The largest scale, the mesoscale, encompassed a region of Northwest Minnesota including Mahnomen, Norman, and Polk Counties. Sixty commercial spring wheat fields in these counties were surveyed for the incidence and severity of FHB in both 2001 and 2002. These fields were selected from a larger survey of 100 fields covering the entire Red River Valley region (29) because a detailed knowledge of cropping history and management practices was available for each field. Fields were surveyed for disease incidence (DI) and disease severity (DS) by assessing 20 groups of five adjacent heads from within a 0.4-ha (1-acre) area sampled corner-to-corner in an X-shaped pattern. The sampled area was located 100 m into the field from a field edge or field access. DI was expressed as the number of heads exhibiting characteristic FHB symptoms (23,26) out of 100 heads assessed, and disease severity

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was the percentage of symptomatic spikelets in the sample. Although information on DS was collected, testing distributions of DS were problematical due to the large error associated with assessing DS (20). Therefore, all analysis of distribution was performed on DI only.

The full-field scale was a 32.4-ha (80-acre) commercial wheat field. Nine fields were analyzed at this scale in each year. Forty-five assessments were made at the linear intersections of a 1-ha grid that was

superimposed on the field (Fig. 1). Intersections on the field edges were included; these assessments were 6 m in from the field edge. Assessments at each point were made by scoring FHB in 10 consecutive wheat heads in two adjacent drill rows. In each year, three fields had wheat as the previous crop, three had soybean, and three had sugar beet.

The microscale consisted of three grids of different sizes that were nested within each other using the same center point

(Fig. 2). The area of the largest grid was 6,561 m² and consisted of quadrats that were 81 m². The second level had an area of 729 m² and consisted of quadrats that were 9 m². The smallest level had an area of 81 m² and consisted of quadrats that were 1 m². Assessments were made in the same manner as used in the field-scale sampling. Although grids were located randomly in each field, grid sites were chosen in areas of uniform stand and were away from field edges. Three of the nine

Fig. 1. Sampling design for full-field scale (32.4-ha) estimates of Fusarium head blight incidence. Each circle represents a sampling point where 20 heads were assessed for disease incidence (DI). The DI for each sampling area is depicted in grayscale. Field A is field #3, field B is field #13, and field C is field #9 (Table 1). P.C. = previous crop.

Fig. 2. Sampling design for the microscale estimates of Fusarium head blight incidence. Three 9-by-9 matrices were sampled in a nested design at each site. Individual quadrat sizes within respective matrices were 91, 9, and 1 m², from left to right. The disease incidence for each square in field #9 (Table 3) is depicted by grayscale.

full fields surveyed were analyzed at this microscale in each year. In each year, one plot was located in a field where wheat was the previous crop, one had soybean, and one had sugar beet.

The adjacent-head scale was a single drill row (10 m in length) from which 60 consecutive wheat heads were assessed for FHB in each of three transects as subplots of the same row. In all, 132 of these transects from 44 drill rows in eight different field plots were analyzed. The plots were established at three Minnesota locations, (Crookston, Morris, and St. Paul) and originated as the control treatments from fungicide evaluations conducted between 1994 and 1997 (16). The data sets include two wheat cultivars, Norm (FHB susceptible) and 2375 (moderately FHB susceptible).

Spatial analysis. For the three largest spatial levels, the point pattern (aggregation within sampling areas) was assessed by comparing the frequency distribution of diseased heads (incidence) to the binomial and β -binomial distributions using BBD version 1.3 (19). This program computes the χ^2 probability that the observed frequency distribution is the same as the theoretical distribution. Agreement with the binomial distribution suggests a random pattern, whereas agreement with the β -binomial distribution suggests an aggregated pattern. From this test, aggregation would suggest that diseased wheat heads are grouped with other diseased heads in a minority of samples (clusters) (20). The index of aggregation (θ) and index of dispersion (D) also were calculated at the three largest spatial levels. These two parameters describe the intensity of aggregation and variation in DI between samples, respectively. Higher values indicate greater aggregation for both parameters (20). The point pattern for the fourth level, adjacent heads, was not evaluated, because the data is only one-dimensional.

Moran's I was used to determine lag autocorrelation (aggregation between samples) at the three largest spatial levels. Lag autocorrelation describes the probability that samples will be associated with samples of similar DI at specified distances. A Moran's I of 0 indicates that the DI of one sample has no effect on the DI of other samples at the specified distance. As Moran's I approaches 1 or -1, the probability increases that the DI of one sample increases or decreases, respectively, the likelihood that samples at the specified distance will have a similar DI (6).

To perform lag autocorrelation at the mesoscale, each field was assigned an X, Y coordinate on a grid that was overlain onto the region. The grid had points every 0.8 km (0.5 mile). Twelve 0.8-km lags were analyzed. Lag autocorrelation was performed on the full-field scale and the microscale data sets using sampling points as lag distances. Five lags were tested for each of these levels. Moran's I was calcu-

lated using the Rookcase plug-in for Microsoft Excel (24). Autocorrelation in the adjacent head study was tested only at the first lag (neighboring heads). This was done by mean runs analysis, which determines the level of autocorrelation in one-dimensional spatial scales (21). This analysis was performed on 132 transects with Statistix (version 7.0, Analytical Software, Ft. Lauderdale, FL).

The full-field scale had an additional analysis conducted to determine how DI changes with distance from the field edge. Each sample was given an X, Y coordinate from the nearest two field edges. A binomial regression using the X distance, the Y distance, and the interaction of the two as predictors was calculated using Arc (version 1.34, University of Minnesota, Minneapolis, MN).

Required sample size. The required sample size (RSS) needed to adequately determine the DI at a precision level of $\pm 5\%$ DI was calculated for each field at the full-field scale. The equation from Southwood (25) to determine the required sample size was $RSS = (t/h)^2 \times \sigma^2$ (eq. 1), where t is the t statistic from student's t distribution at $df = RSS - 1$, h is the precision level of $\pm 5\%$ (2 heads per 20 sampled), and σ^2 is the variance of a theoretical distribution. The variance from the binomial distribution was used to compute RSS for a field if that distribution could not be rejected ($P > 0.05$). The variance from the β -binomial distribution was used if the binomial distribution was rejected. To calculate the appropriate variance for the binomial and β -binomial distribution, equations from Madden and Hughes (20) were used. The RSS equation is solved iteratively until the RSS on the left equals the $df + 1$ for the t on the right. The optimal sample size (OSS) is the average of the RSSs.

To evaluate the accuracy of sample sizes smaller than the OSS, 500 samples ($N = OSS$, $n = 20$) were drawn with replacement from the data for each field. This was repeated with $N = 1$ to 5, generating mean and variance of 500 field means for each sampling size. The procedure was repeated 1,000 times using the resampling plug-in from Microsoft Excel. The mean DI from each resampling (set of 500 samples) for the smaller sample sizes was compared with the DIs generated with the OSS by χ^2 .

RESULTS

Spatial distribution at the mesoscale.

The incidence of FHB in 60 commercial fields averaged 11.3% in 2001 and 14.6% in 2002. The severity of FHB in 60 commercial fields averaged 2.1% (range, 0.1 to 28.3%) in 2001 and 11.0% (range, 0 to 65.0%) in 2002. DI and DS were highly correlated in both years (Pearson's correlation: $r = 0.88$ and 0.92 for 2001 and 2002, respectively). A map of the field locations with their DIs is shown in Figure 3.

In both years, the frequency distributions of FHB DI at the mesoscale could not be described by the binomial distribution ($P < 0.001$). However, the β -binomial distribution was appropriate (2001 and 2002, $P = 0.872$ and 0.779 , respectively) as a model for FHB DI distribution across the region in both years. For both years, the θ value also showed the distributions to be more significantly aggregated than random, but the level of aggregation was small in both 2001 ($\theta = 0.08$) and 2002 ($\theta = 0.06$). The variation between samples also was significantly greater than in a random distribution (2001, $D = 10.43$ and $P < 0.001$; 2002, $D = 8.04$ and $P < 0.001$). Lag correlation using Moran's I was not significant at 11 of the 12 lags tested. Only the third lag, 1.2 km, showed significant autocorrelation (2001 and 2002, $I = 0.827$ and 0.983 , respectively). This suggests that FHB DI was aggregated on an individual field basis (some fields had DI significantly higher and lower than the area mean), and that DI of one field did not impact the DI of other fields.

Spatial pattern at the full-field scale.

Fits to theoretical distributions and tests for departure from randomness showed a random to slightly aggregated pattern at the full-field level in both years, depending on the previous crop (Tables 1 and 2). The binomial distribution could not be rejected for 13 of the 18 fields ($P > 0.05$). In the five fields where the binomial distribution could be rejected, wheat was the previous crop in three of them. These three fields also had among the highest DIs (33.2, 44.1, and 56.2%) of all fields sampled in both years (Table 1). Soybean was the previous crop for the remaining two fields, for which the binomial distribution could be rejected, and these fields had moderate DIs (14.7 and 15.8%; Table 1). The index of dispersion (D) at the full-field level showed that 11 of 18 fields had a variance in DI that was significantly greater ($P < 0.05$) than the binomial distribution (Table 1). In 10 of these fields, wheat or soybean was the previous crop. Five of the six fields that had sugar beet as the previous crop had variances equal to or lower than the binomial distribution. This indicates that previous crop affected the level at which diseased wheat heads are aggregated (wheat > soybean > sugar beet).

Lag correlation tests conducted with Moran's I showed that 9 of 18 fields had significant positive autocorrelation at the first lag (Table 1). Four of these fields previously were planted to wheat, four to soybean, and one to sugar beet. The fields with significant autocorrelation at the first lag had low Moran's I values ranging from 0.209 to 0.500. Autocorrelation at the second lag was very low or negative in all cases (*data not shown*). These results indicated that the DI at one sampling point may have some effect on the DI of neighboring sampling points under

Fig. 3. Incidence (%) of Fusarium head blight in 60 fields of spring wheat from three counties in northwest Minnesota assessed in 2001 (top) and 2002 (bottom). Darker lines are county lines and lighter lines are township borders. Scale: 1 cm = 7 km.

Table 1. Incidence of Fusarium head blight for 18 fields at the full-field scale and fits to the binomial and β -binomial distributions, the aggregation index (θ), the dispersion index (D), Moran's I at the first lag, and the required sample size (RSS)

Field ^a	Previous crop	DI (%) ^b	Binomial ^c	β -Binomial ^d	θ ^e	D ^f	Moran's I ^g	RSS ^h
1	Wheat	21.4	0.097	0.154	0.05 (0.031)	1.86 (0.001)	0.216*	5
2	...	14.4	0.085	0.689	0.04 (0.021)	1.77 (0.000)	0.112	5
3	...	33.2	0.006	0.150	0.10 (0.002)	2.69 (0.000)	0.311*	11
4	Soybean	14.7	0.003	0.020	0.07 (0.019)	2.50 (0.000)	0.211*	7
5	...	17.1	0.118	0.397	0.04 (0.064)	1.89 (0.000)	0.339**	5
6	...	30.5	0.181	0.074	0.01 (0.694)	1.12 (0.279)	-0.031	6
7	Sugar beet	11.8	0.128	—	0.00	0.64 (0.030)	0.209*	5
8	...	23.7	0.644	0.605	0.12 (0.385)	1.26 (0.120)	-0.144	5
9	...	21.4	0.510	—	0.00	0.76 (0.877)	-0.130	5
10	Wheat	44.1	0.000	0.354	0.13 (0.002)	3.25 (0.000)	0.395**	12
11	...	11.4	0.862	—	0.00	1.00 (0.472)	0.130	4
12	...	56.2	0.000	0.019	0.30 (0.000)	5.49 (0.000)	0.399**	17
13	Soybean	24.4	0.572	0.464	0.04 (0.063)	1.65 (0.004)	0.343**	5
14	...	41.0	0.119	0.366	0.04 (0.053)	1.82 (0.001)	0.127	6
15	...	15.8	0.004	0.107	0.08 (0.001)	3.06 (0.000)	0.500**	8
16	Sugar beet	10.6	0.728	—	0.00	0.94 (0.416)	0.065	5
17	...	28.1	0.249	0.357	0.02 (0.255)	1.43 (0.060)	-0.076	6
18	...	18.0	0.788	0.828	0.02 (0.254)	1.45 (0.033)	0.014	5

^a Fields 1 to 9 were sampled in 2001 and fields 10 to 18 were sampled in 2002.

^b DI = disease incidence as a percentage of 900 heads sampled in 45 groups of 20.

^c Values reported are the probability that the data is represented by the binomial distribution.

^d Values reported are the probability that the data is represented by the β -binomial distribution; — indicates that the distribution could not be fit because θ was negative.

^e Aggregation index. Values in parenthesis are the probability that $\theta = 0$.

^f Dispersion index, analogous to the S^2/X . Values in parenthesis are the probability that $D = 1$.

^g Moran's I value for the first lag; * and ** indicate significantly greater than 0 at $\alpha = 0.05$ and 0.001, respectively.

^h RSS to obtain a precision of $\pm 5\%$ DI around the mean.

certain previous crop conditions at the full-field level.

Spatial pattern at the microscale. The binomial distribution could not be rejected ($P > 0.05$) for all 18 grids tested in the microscale (Table 3). The β -binomial distribution could be calculated for 7 of 18 grids. The β -binomial distribution cannot be calculated when θ is negative. In no case was θ significantly greater than zero (Table 3). The level of variance, D, showed that the variation in DI was no different from random in 15 of 18 grids (Table 3). The D values for grids with greater than random variance were low ($D = 1.44, 1.39$, and 1.16). These tests indicate that FHB DI is randomly distributed within the sampling areas at the microscale (0.66 ha or less).

Lag correlation showed that 16 of the 18 microscale grids lacked autocorrelation at the first lag (Table 3). The Moran's I values for grids with significant autocorrelation at the first lag were low ($I = 0.185$ and 0.174). No significant autocorrelation was seen at lag distances of two through five in any of the microscale data sets (*data not shown*). This suggested that the DI of one sampling point did not affect DI of the other sampling points at all three levels of the microscale.

Spatial analysis of row data. The DI for the 132 transects analyzed was 66.7% (range, 27.2 to 98.7%). Runs analysis suggested randomness (significantly no fewer runs [$P > 0.05$] than would be expected by a random distribution) in 114 of 132 (86.4%) transects. This was the case for both high (90%) and moderate (30%) DI, and applied to both the susceptible cv. Norm and the moderately susceptible

cv. 2375. These results demonstrated that even at high to very high levels of DI, one wheat head did not influence the DI of neighboring wheat heads, and suggested the absence of a functional secondary disease cycle in spring wheat.

Test for field edge effects. Binomial regression to determine how DI changed as distance from the field edge increased showed no edge effect (Fig. 2). In 2001, no fields had a change in DI in any direction from any edge ($P > 0.05$). In 2002, six of the nine fields also showed no change in DI as the distance from an edge increased. In three cases (Table 1, fields 9, 11, and 18), DI increased significantly from the outer edge to the next sampling point into the field. This suggests that local inoculum originating outside the field did not affect DI at the edges of the field in these 18 cases.

RSS. The average RSS for six fields where wheat was the previous crop was 10 samples and the average RSS for fields with other previous crops (soybean and

sugar beet) was 6 samples. The average RSS for all 18 fields (optimal sample size) was seven samples. There was rarely a significant difference in DI from sample sizes smaller than the OSS ($N = 1$ to 5) when they were compared with the DI produced by using the OSS value by χ^2 (data not shown). Based on these results, seven 20-head samples should adequately determine the incidence of FHB in commercial fields of spring wheat.

DISCUSSION

At the mesoscale level, the incidence of FHB by field was more significantly aggregated than random; however, lag correlation showed that DI in one field had no relationship to DI in adjacent fields based on proximity. This suggests that certain factors within fields contribute to a DI that is higher or lower than the regional mean. In 2002, fields that had wheat as the previous crop had a higher DI than fields that had any other previous crop (29). It is likely that infected wheat residue contrib-

uted to increased FHB DI as over-wintered inoculum. The effects of wheat and corn residue on the development of FHB are well documented (1,8,15,23). Other factors, such as precipitation amounts and anthesis date, which were not evaluated here, also may have influenced DI in an individual field. All fields used in this study were planted to cultivars categorized as moderately susceptible to FHB (28); therefore, cultivar effects were not likely a major factor in contributing to observed differences. Growers in the Red River Valley have adopted moderately susceptible cultivars and excluded susceptible cultivars as a response to recent and severe epidemics (23).

The results of mesoscale analysis suggest important implications for FHB management in the Red River Valley. Because of the observed between-field variability, in-season management decisions, such as fungicide sprays, should take into account factors unique to each field, including residue from the previous crop and its likelihood of harboring effective inoculum. Although small plot studies showed only modest (but significant) differences in DI as a result of moldboard plow treatment compared with using a chisel plow (8), the destruction of infected residue remains an important management tool for the control of FHB in Minnesota.

At the full-field level, aggregation was affected by previous crop, with wheat showing the most aggregation. It is possible that part of this aggregation may have been the result of the redistribution and aggregation of wheat residue from the last

Table 2. Effect of previous crop on the point pattern and lag correlation of Fusarium head blight incidence at the full-field scale with average disease incidence (DI), dispersion index (D), and Moran's I for each previous crop

Previous crop	DI (%) ^a	Point pattern ^b	Autocorrelation ^c	D ^d	Moran's I
Wheat	30.1	3/6	4/6	2.68	0.239
Soybean	23.9	4/6	4/6	2.01	0.248
Sugar beet	18.9	6/6	1/6	1.08	-0.226

^a Disease incidence as a percentage of 5,400 heads sampled from 6 fields in 45 groups of 20.

^b Number of fields where the binomial (random) distribution could not be rejected of the total fields sampled.

^c Number of fields with significant Moran's I values at the first lag of the total fields sampled.

^d Dispersion index, analogous to the S^2/X .

Table 3. Incidence of Fusarium head blight for six fields sampled at the micro-scale with nested quadrats and fits to the binomial and beta-binomial distributions, the aggregation index (θ), the dispersion index (D), and Moran's I at the first lag

Year, previous crop	Quadrat size (m ²) ^a	DI (%) ^b	Binomial ^c	β -Binomial ^d	θ^e	D ^f	Moran's I ^g
2001							
Wheat	1	8.6	0.473	—	0.00	0.98 (0.470)	0.185*
	9	9.6	0.178	0.096	0.03 (1.000)	1.15 (0.169)	-0.060
	81	8.0	0.845	0.772	0.00 (0.770)	0.86 (0.190)	0.060
Soybean	1	1.5	1.000	—	0.00	1.01 (0.454)	0.007
	9	1.5	1.000	0.956	0.01 (0.538)	1.06 (0.336)	-0.036
	81	1.3	1.000	—	0.00	1.09 (0.272)	0.016
Sugar beet	1	0.8	1.000	—	0.00	1.01 (0.454)	-0.007
	9	1.7	1.000	0.874	0.00 (1.000)	1.04 (0.381)	0.124
	81	2.2	0.747	0.994	0.02 (0.118)	1.44 (0.006)	-0.014
2002							
Wheat	1	29.7	0.526	—	0.00	0.79 (0.084)	-0.019
	9	31.7	0.721	—	0.00	0.96 (0.419)	0.068
	81	32.4	0.347	0.097	0.02 (0.070)	1.39 (0.000)	0.174*
Soybean	1	22.7	0.428	0.404	0.01 (0.399)	1.16 (0.000)	0.067
	9	21.7	0.300	—	0.00	0.99 (0.496)	0.071
	81	21.7	0.132	—	0.00	0.90 (0.274)	-0.104
Sugar beet	1	25.1	0.484	—	0.00	0.82 (0.123)	0.032
	9	22.7	0.706	—	0.00	0.80 (0.096)	0.017
	81	18.3	0.497	—	0.02	0.73 (0.054)	-0.029

^a Individual quadrat size of 9-by-9 sampling grids whose overall size was 9, 729, and 6,561 m², respectively.

^b Disease incidence as a percentage of 1,620 heads sampled in 81 groups of 20.

^c Values reported are the probability that the data is represented by the binomial distribution.

^d Values reported are the probability that the data is represented by the β -binomial distribution; — indicates that the distribution could not be fit because θ was negative.

^e Aggregation index. Values in parenthesis are the probability that $\theta = 0$.

^f Dispersion index, analogous to the S^2/X . Values in parenthesis are the probability that $D = 1$.

^g Moran's I value for the first lag; * indicates significantly greater than 0 at $\alpha = 0.05$.

growing season. Soils in the Red River Valley are generally heavy clay-loam and are prone to flooding that results in both run-off and ponding. Wheat residue can collect in natural drainage lanes or low spots. Visual observation of the distribution of wheat residue in the spring shows that it often is more aggregated than at any other time after harvest. This tendency was noticed by Holbert et al. (15), who showed that DI was higher around areas where residue collected. This aggregation in fields planted to successive wheat crops, as well as the absence of an edge effect, support the idea that a significant amount of primary inoculum originate within the field (11,12,26) and reflect positively on the value of rotation and tillage as management tools.

In our study, slight and no aggregation was seen when soybean and sugar beet, respectively, were the previous crops. Fernandez (10) isolated *F. graminearum* from soybean residue pieces when soybean was planted after wheat. She also observed higher levels of FHB infection from planting wheat into *F. graminearum*-colonized soybean residue. This is not because *F. graminearum* is a primary pathogen of soybean but, rather, because soybean is a reasonably good substrate for saprophytic colonization (10). In the current study, some fields that were planted after soybean had low levels of aggregation. This may have been due to saprophytic colonization of the soybean residue or the survival on infected residues for >1 year. FHB in wheat fields following sugar beet did not show signs of aggregation. Sugar beet is not known to be a pathogenic or saprophytic host of *F. graminearum*.

Previous studies of the spatial distribution of FHB have reported randomness at small spatial scales. In a 3-year study, Del Ponte et al. (7) assessed DI in 60 0.09-m² quadrats at least 5 m from each other. Of the 70 fields in those 3 years, 64 had a random distribution of DI. El-Allef et al. (9) examined two fields that were 100-m² grids of 1-by-1-m quadrats. They reported that point patterns in one of the two fields were random, whereas disease distributions in the second field showed aggregation. Comparable plot sizes in this study (81 and 729 m²) showed FHB to be randomly distributed within samples and between samples in all cases. Moreover, FHB in this study was random regardless of previous crop, cultivar, DI, or DS (from low to high incidence and severity), including among adjacent heads. This suggests that FHB was functionally acting as a monocyclic disease.

We conclude that in-field crop residue was the most important factor contributing to the incidence and aggregation of FHB in the fields we sampled in 2001 and 2002.

The aggregation of DI at the mesoscale level (high-DI fields adjacent to low-DI fields) suggests that individual fields should be evaluated to estimate disease risk and make management decisions, as opposed to using regional predictors. Regional risk predictors (13) may contribute integrated meteorological information useful to growers, but inoculum measures (spore trapping data representing only a limited number of sites) cannot be the basis for management decisions in individual fields. Furthermore, a better understanding of the specific quantities of infested residues needed to initiate significant levels of infection would contribute greatly to successful tillage and residue management actions to better manage FHB in a reduced-till environment.

To sample fields optimally, seven 20-head samples should be taken in an area that is representative of the field. When costs are prohibitive, fewer samples can be effective at estimating incidence of FHB in spring wheat in the Red River Valley. Sampling more fields would provide a better regional estimate of FHB compared with intensively sampling fewer fields.

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